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Load separation in 17 mm wide CT specimen of Zr-2.5Nb pressure tube material

A. K. Bind[a,b]*, S. Sunil[a], R. N. Singh[a,b], Abhishek Tiwari[b], J. K. Chakravartty[a],

[a]*Bhabha Atomic Research Centre, Trombay, Mumbai-400085,India*
[b]*Homi Bhabha National Institute, Anushakti Nagar, Mumbai-400094, India*

Abstract

In PHWR community 17 mm wide curved compact tension (CCT) specimen is most commonly used for fracture toughness testing in axial direction of pressure tube. This specimen geometry is different from Conventional CT specimen (ASTM E 1820–11) in two aspects. First being the curvature of the CCT specimen and second is that it does not meet the alternate thickness criteria of $2 \leq W/B \leq 4$ for B = 3.6 mm. Despite these differences, the eta and gamma factors used for the fracture toughness measurement of Conventional CT specimen according to ASTM E 1820 –11 are also applied for CCT specimen. In this work, 17 mm wide blunt notched Conventional CT specimens of Zr-2.5Nb pressure tube with different a/W ratios between 0.3 and 0.7 were loaded up to maximum load. The load separabilty was checked and eta factor was calculated using load separation method. The investigation of separation parameter (S) for reference cracks (a_i/W) between 0.45 and 0.7 showed that (a) load was separable over whole range of plastic displacement for the CT specimens with a_i/W between 0.45 and 0.7, except for small initial inseparable region, and (b) load was not separable over whole range of plastic displacement for the CT specimens with a_i/W of 0.35 and 0.40. The small inseparable region in the CT specimens with a_i/W between 0.45 and 0.7 is reported in literature to be due to initial blunting of the CT specimen. The eta factor, calculated using load separation method proposed by Sharobeam and Landes, was found to have a constant value of 2.08 for a_i/W in range of 0.45 and 0.70. The eta factor was found to be lower than that reported by Sharobeam and Landes as well as in ASTM 1820 – 11. Since load was not separable for CT specimens with a/W of 0.35 and 0.4, eta factor derived for this CT geometry cannot be used for a/W below 0.45.

Keywords: PHWR; curved CT; load separation; separtion parameter; eta factor

* Corresponding author. Tel.: +91-22-2559-2170; fax: +91-22-2550-5151.
E-mail address: akbind@barc.gov.n

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1. Introduction

Pressure tubes (PT) made of Zr-alloys act as miniature pressure vessel in Pressurized Heavy Water Reactor (PHWR) with coolant heavy water flowing through it under a pressure of around 10 MPa and at temperatures in the range of 253 to 293 °C (Dietz 1994; Lamaignan and Motta 1994; Coleman et al. 1996). Since pressure tubes act as the final pressure boundary for hot coolant in PHWRs, their integrity is to be maintained not only during reactor operation but also under accidental conditions (Field et al. 1985; Puls 1997; Maon and Richinson 1993). Safety plans of the PHWR assume leak before break (LBB) criteria regarding the pressure tubes. To meet LBB criteria, the critical crack length (*CCL*) causing catastrophic failure of the pressure tube should be sufficiently large. The fracture toughness in the form of *J-R* curve and single value is used for the *CCL* calculation (Singh et al. 2013; Bind et al. 2014; Bind et al. 2015; Dubey et al. 1999).

Nomenclature

a	crack length, distance of crack tip from the centre of loading pins
B	thickness of the CT specimen
b	un-cracked ligament, W-a
CCL	critical crack length
G	specimen geometrical function
H	material deformation function
P	load
S_{ij}	separation parameter of crack length, a_i for reference crack, a_j
W	width of the CT specimen
δ_{pl}	plastic deformation
η_{pl}	plastic eta factor
γ_{pl}	plastic gamma factor

The pressure tube thickness (3.6 mm for 220 MW and 4.5 mm for 540 MW) is not sufficient to get a conventional CT specimen directly from the pressure tube which is able to meet the thickness criteria of ASTM standard E1820-13. The conventional CT specimen can be made from the pressure tube after cold flattening the pressure tube. However, mechanical properties of the pressure tube may change after cold flattening. To avoid any change in mechanical properties due to cold flattening, curved CT (CCT) specimens are cut directly from the pressure tube for fracture toughness evaluation in axial direction of the pressure tube (Singh et al. 2013; Bind et al. 2014; Bind et al. 2015; Dubey et al. 1999). In PHWR community, 17 mm wide CCT specimens are most widely used for fracture toughness evaluation in axial direction of the pressure tube (Singh et al. 2013; Bind et al. 2014; Bind et al. 2015; Dubey et al. 1999). CCT specimen of 17 mm width is different from conventional CT specimen recommended by ASTM E1820-13in two ways. First difference is the curvature of CCT specimen and second difference is that it does not meet the $W/B=2$ thickness criteria. For 220 MW pressure tube, the CCT specimen also does not meet alternate thickness criteria of $2 \leq W/B \leq 4$. For 540 MW pressure tube, W/B is approximately 4. Despite aforementioned differences, η_{pl} and γ_{pl} factors of conventional CT specimen are used for the CCT specimen (Singh et al. 2013; Bind et al. 2014; Bind et al. 2015; Dubey et al. 1999). As per authors' best knowledge, η_{pl} and γ_{pl} factors for CCT specimen are not available in open literatures. Using simple bending theory, it was shown that there would be little effect of curvature on stress distribution of CCT specimen and so, η_{pl} and γ_{pl} factors for the conventional CT specimen can be used for CCT specimen without any significant error (Chow and Simpson 1988).

The purpose of this work was to address second issue of CCT specimen i.e. to calculate η_{pl} factor for conventional CT specimen of Zr-2.5Nb pressure tube material just meeting the alternate thickness criteria of CT specimen recommended by ASTM E 1820-13. The η_{pl} factor for conventional CT was calculated using load separation method using blunted notch specimens having a/W between 0.35 to 0.70 with an interval of 0.05.

2. Material and method

2.1 Material

Quadruple melted and CWSR 540 MWe pressure tube material having an inner diameter of 103 mm and thickness of 4.5 mm was used in this study. A spool of about 100 mm was cut from the tube and slit in two pieces at 180°. Each piece was warm rolled in to plate at 400 °C. After rolling thickness was reduced to 4.25 mm. 17 mm wide conventional CT specimens (fig 1a) with *a/W* between 0.35 to 0.70 in the step of 0.05 was cut from the rolled plate with crack oriented in axial direction of the pressure tube. All the blunt conventional CT specimens were pulled up to maximum load using Zwick-Roell screw driven UTM. To avoid any crack growth during the tests, pulling was stopped at maximum load.

2.2 Load separation method

For existence of η_{pl}, load (P) is to be represented as separable form i.e. P is a separate function of specimen geometry and material deformation (Paris et al. 1980). If for certain material and geometry, P is separable in plastic region, it can be represented as equation (1).

$$P = G\left(\frac{a}{W}\right)H\left(\frac{\delta_{pl}}{W}\right) \tag{1}$$

Where δ_{pl} is plastic displacement. For P-δ_{pl} curve of two different specimens of different stationary crack lengths a_i and a_j as shown in fig. 1b, separation parameters S_{ij} is defined as $P(a_i)/P(a_j)$ at constant δ_{pl}.

$$S_{ij} = \left.\frac{P(a_i,\delta_{pl})}{P(a_j,\delta_{pl})}\right|_{\delta_{pl}} = \frac{G\left(\frac{a_i}{W}\right)H\left(\frac{\delta_1}{W}\right)}{G\left(\frac{a_j}{W}\right)H\left(\frac{\delta_1}{W}\right)} = \frac{G\left(\frac{a_i}{W}\right)}{G\left(\frac{a_j}{W}\right)} \tag{2}$$

Equation (2) shows that S_{ij} is independent of δ_{pl} and is constant for fixed values of a_i and a_j. In other words, if S_{ij} is constant over whole range of δ_{pl}, then the load can be represented by a separable form.

Using two forms of J_{pl}, $-\left.\frac{\partial U_{pl}}{\partial A}\right|_{\delta_{pl}}$ and $\frac{\eta_{pl}A_{pl}}{Bb}$ and Equation (1), Sharobeam and Landes (1991) derived the relation between η_{pl} and $G\left(\frac{b}{W}\right)$ as given by:

$$\eta_{pl} = \frac{b}{W}\frac{dG\left(\frac{b}{W}\right)\Big/ d\left(\frac{b}{W}\right)}{G\left(\frac{b}{W}\right)} \tag{3}$$

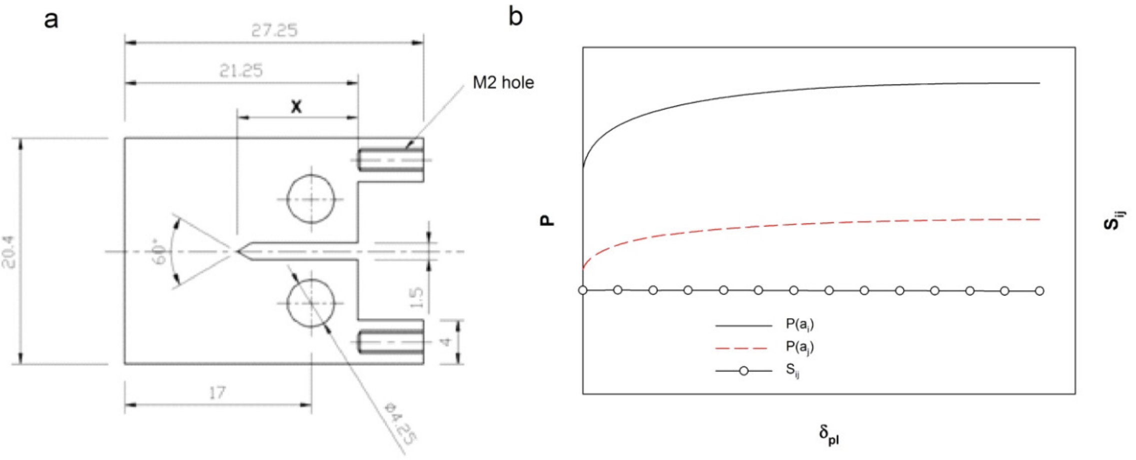

Fig. 1.(a) Drawing of 17 mm conventional CT specimen; (b)P-δ_{pl} for two crack a_i, a_j and corresponding S_{ij}.

They also showed that for all the configurations, S vs. b/W curves showed the power law variation and using equation (3) they found that for a given reference crack, a_j, the η_{pl} equalled to power law exponent (m). For a given crack length, a_j, the η_{pl} was calculated using power law fitting of S vs. b/W ; the a_j was used as reference crack to calculated the S for all crack lengths.

3. Result

For each test, the δ_{pl} was calculated after subtracting the elastic displacement using the compliance measured from the test. The P-δ_{pl} curves for the all tests are shown in Fig. 2a. The separation parameters S_{ij} were calculated for all the possible combinations of a_i/W and a_j/W values all over the plastic displacement range. The variation of the S_{ij} for different a_i/W for the reference crack a_j/W of 0.70 is shown in fig. 2b. For a_i/W of 0.45 and above, the S_{ij} was constant over whole range of the δ_{pl} except for a small region at the beginning of plastic deformation. For a_i/W below 0.45, the S_{ij} was not constant over whole range of plastic deformation. Similar curves were also observed for the reference cracks, a_j/W between 0.45 and 0.65.

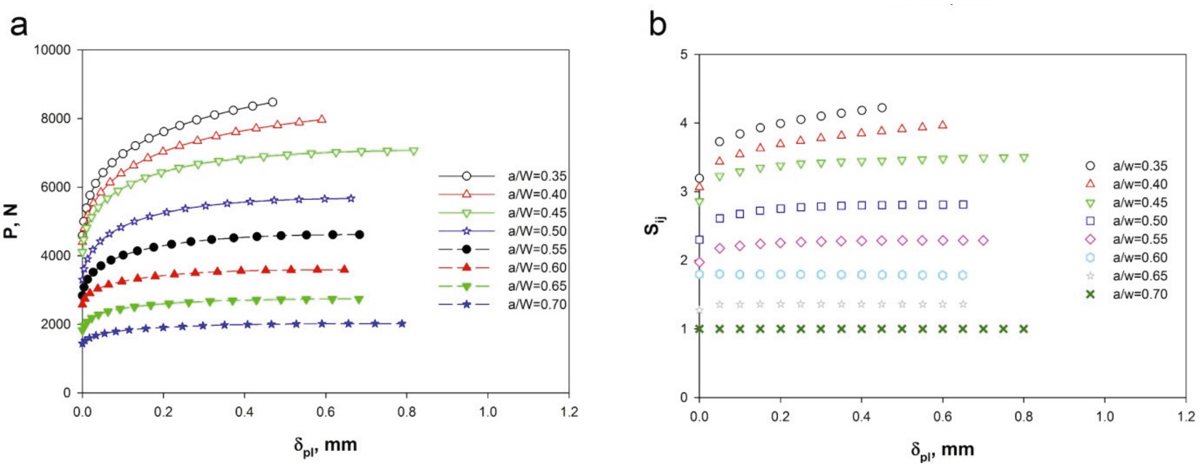

Fig. 2. (a) P-δ_{pl} curve of the conventional CT specimens with different crack length; (b) S_{ij}-δ_{pl} curve of the conventional CT specimens with different crack lenthfor a refecence crack, a_j/W of 0.70.

The variation of S_{ij} with b_i/W for different reference cracks, b_j/W between 0.30 and 0.55 (a_j/W between 0.45 and 0.70) are shown in fig. 3a on log-log scale. Because of non separability, the data of b_j/W of 0.60 and 0.65 (a_j/W 0.35 and 0.40) was not included in fig. 3a. Also S_{ij}-b_i/W curve for the reference cracks, b_j/W of 0.60 and 0.65 (a_j/W 0.35 and 0.40) was not plotted the fig 3a. All the curves are linear on log-log scale indicating power law fit the best for these curves. The S_{ij}-b_i/W curve for each reference crack, b_j/W was fitted with a power law fit and the η_{pl} was evaluated as described by Sharobeam and Landes [13]. The variation of the η_{pl} with b_i/W was shown in fig. 3b along with η_{pl} data reported by Sharobeam and Landes [13] and ASTM 1820-13.The η_{pl} was found to be constant for b_i/W between 0.30 and 0.55 and was equalled to 2.08.

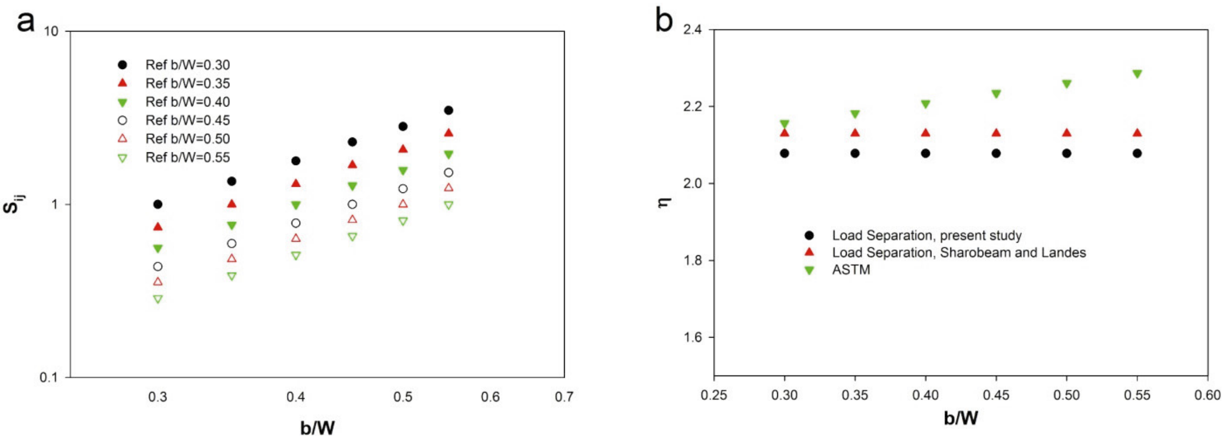

Fig. 3. (a) S_{ij} vs. b/W curveof the conventional CT specimens for different reference cracks (b) Comparison of the η_{pl} of conventional CT specimen calculated using load separation method with ASTM 1820-13.

4. Discussion

For a given geometry of fracture test, we should know whether load separabilty exists or not. The existence of load separability is pre-requisite for existence of the η_{pl} factor for any fracture test geometry (Paris et al. 1980). If load separability exists for the given fracture test geometry, it may not exist for whole range of a/W. For a/W below 0.45, S_{ij} was not constant over whole range of the plastic deformation (fig. 2b) indicating non separability of load for a/W below 0.45. This indicates non existence of the η_{pl} for a/W below 0.45. It means that the initial a/W of the specimens should be at least 0.45. For a/W of 0.45 and above, $S_{ij}$was constant over whole range of the plastic deformation except for a small region at the beginning of plastic deformation (fig. 2b). The constant value of S_{ij} means that the load was separable indicating load separability for a/W of 0.45 and above. The S_{ij} of all a_i/W did not show any decline after reaching constant value (fig. 2b). No decline in S_{ij} is an indication of no crack growth during the test in all specimens up to maximum load (Sharobeam and Landes 1991). In present work, η_{pl} was constant for a/W between 0.45 to 0.70 and it was found to be 2.08. For same configuration using load separation method, Sharobeam and Landes (1991) also reported the constant behaviour of η_{pl} over a range of a/W and it was 2.13. But there was two difference in specimen geometry used by us and Sharobeam and Landes (1991); (a) Sharobeam and Landes (1991) used W/B~2 [13] whereas in our work we used W/B=4, specimens were just meeting the alternate thickness criteria of ASTM E 1820-13 and (b) the notch radius used by Sharobeam and Landes (1991) was 1 mm [13] where in our work it was about 0.15 mm, about half of dia. of wire used during EDM wire cut. Since there was no crack growth as indicated by no decline in the values of S_{ij}, it may be concluded that the difference in η_{pl} values as reported by us and Sharobeam and Landes (1991) is not due to difference in notch radius used. So, the difference in η_{pl} values as reported by us and Sharobeam and Landes might be due to difference in W/B of the specimens used in two works.

5. Conclusion

17 mm blunt notched conventional CT specimens of Zr-2.5Nb pressure tube with different *a/W* ratios between 0.35 to 0.70 were used to check load separability and to calculate the η_{pl} using load separation method. The load separability existed for *a/W* between 0.45 to 0.70 except for small initial inseparable region. The η_{pl} calculated using load separation method was found to have a constant value of 2.08 for *a/W* between 0.45 to 0.70 and was slightly lower than that of 2.13 as reported by Sharobeam and Landes. The difference in the η_{pl} values was attributed to the difference in *W/B* ratio of the specimens used in present work and Sharobeam and Landes work. Because of non separability, the values of η_{pl} reported in this work cannot be used for specimens with initial *a/W* less than 0.45.

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